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A METHOD FOR THE CORRECTION OF FINITE RISE TIME EFFECTS IN THE CHARACTERIZATION OF NON LINEAR VISCOELASTIC MATERIALS

BY E. G. POWELL

RESEARCH AND TECHNOLOGY DEPARTMENT

FEBRUARY 1981

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NSWC/MP-81-67	2. GOVT ACCESSION NO. AD-A100 591	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) A Method for the Correction of Finite Rise Time Effects in the Characterization of Non Linear Viscoelastic Materials		5. TYPE OF REPORT & PERIOD COVERED Final Report Oct 80 — Jan 81
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) E. G. Powell		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Surface Weapons Center White Oak Wilver Spring, Maryland 20910		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS O;
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE February 1981
		13. NUMBER OF PAGES 10
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Prepared at the request of the Naval Ordnance Station, Indian Head, Maryland

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Rocket Motors
Rocket Propellant
Viscoelastic
Nonlinear

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A method is presented here for the correction of the effect of finite rise time upon stress relaxation experiments. The basis for the correction relies on the Farris nonlinear homogeneous theory. In the limit of zero nonlinearity the correction is shown to agree with the correction by linear theory. In the limit of very strong nonlinearity the correction is achieved by redefining the zero of time to be at the end of the rise time.

FOREWORD

This report was prepared at the request of Mr. John Kelly, Naval Ordnance Station, as a justification for the commonly used engineering approximation of taking the stress relaxation time zero from the termination of the strain ramp. Although the extent of applicability of the Farris theory has been called into question recently, use of this report's rise time correction based on the Farris theory permits nearly an order of magnitude improvement in the useful short-time stress relaxation data.

J. F. PROCTOR
By direction

CONTENTS

	Page
Introduction.	5
Derivation of the Correction.	5
Comparison with Linear Theory	7
Summary	7
Recommendations	7

INTRODUCTION

The characterization of viscoelastic materials usually requires measurement of stress relaxation while the specimen is held at a constant strain. A practical problem encountered in the interpretation of these data is accounting for the effect of finite rise time of the applied strain. For a variety of reasons, either instrumental or procedural, the rise time cannot be made very short. One common approach to the problem simply ignores data acquired soon after the full constant strain level is achieved. However this throws away nearly a decade of potentially useful data about the short-time behavior. For the case of linearly viscoelastic materials and for a linear ramp to full strain, there exists the well-known correction of taking the zero of time from the mid-point of the ramp. In practice this is most useful for unfilled polymers. We derive here a more general correction which applies to the Farris theory of viscoelasticity[1]. The correction has been found to apply to solid rocket propellant.

DERIVATION OF THE CORRECTION

The Farris theory preserves one of the two requirements for linearity, homogeneity, but permits the other requirement, superposition, to have a particular non-linear form. This theory is usually applied to solid rocket propellants which are filled polymers with permanent memory. The phenomenon of permanent memory is physically modeled by assumptions about cumulative damage and is mathematically implemented by a functional of strain history. The functional of strain history is the Lebesque norm, $||\varepsilon||_p$, of strain from the zero point in time to the present:

$$||\varepsilon||_p = \left[\int_0^t |\ \varepsilon\ (x)\ |^p\ dx\right]^{1/p}\ ,\ p \geqq 1$$

[1]Farris, R. J., "Homogeneous Constitutive Equations for Materials with Permanent Memory", PhD Dissertation, College of Engineering, University of Utah, 1970.

where ε is the uniaxial strain and p is a parameter of the theory which measures the degree of nonlinearity.

Details of the theory can be found in reference (1), so we start here with a result of the theory which gives the stress, σ, of an isothermal uniaxial specimen:

$$\sigma(t) = E\,\varepsilon \left(\frac{|\varepsilon|}{||\varepsilon||_p} \right)^m$$

We derive a correction for a finite rise time, T, by calculating the stress at a time, $t > T$, where the strain history is

$$\begin{array}{ll} \varepsilon = 0 & t < 0 \\ \varepsilon = Rt & 0 \leq t \leq T \\ \varepsilon = RT & t \geq T \end{array}$$

and where R is the strain rate of the ramp. Thus, splitting the functional into two parts for the two non-zero domains of definition we have:

$$\varepsilon\,(t) = E\,R\,T \left(\frac{|\,R\,T\,|}{\left[\int_0^T |\,R\,t\,|^p\,dx + \int_T^t |\,R\,T\,|^p\,dx \right]^{1/p}} \right)^m$$

which reduces to

$$\sigma(t) = E\,\varepsilon_0 \left\{ \frac{1}{\left[-T\left(\frac{p}{p+1}\right) + t \right]^{1/p}} \right\}^m$$

The desired correction is achieved by noting that, if the zero of time is redefined to start at $t = \left(\frac{p}{p+1}\right) T$, then exactly the same result is obtained as if the experiment had been conducted with a truly zero rise time.

COMPARISON WITH LINEAR THEORY

Note that in the limit $p \to 1$ the correction reduces to the linear viscoelastic correction derived by Farris (1). In the limit $p \to \infty$ the correction implies that the zero of time is taken from the time of ramp termination. In fact, materials with a high degree of solids loading often give the straightest line on a log-log plot when the ramp termination is taken as the zero point of time. This agrees with the observations of Farris indicating that p is frequently large, often exceeding three and sometimes becoming as large as twenty.

SUMMARY

In the Farris model of nonlinear viscoelasticity, the effect on a stress relaxation experiment of a finite rise time, T, can be corrected by taking the zero of time at

$$t' = \left(\frac{p}{p + 1}\right) (T) \qquad 1 \geq p \geq \infty$$

from the beginning of the ramp. Since p>>1, this constitutes a justification of the common engineering practice of taking the zero of time from the end of the ramp.

RECOMMENDATIONS

In recent years the range of applicability of the Farris theory has been questioned, however the field of nonlinear viscoelasticity is very difficult and remains incompletely developed. Therefore it is recommended additional study of rise time effects be done when a fully satisfactory theory arrives. Prof. R. Schapery of Texas A and M University continues to develop his thermodynamic theory[2]. Because of the fundamental basis of that work we recommend further that particular attention be given to Prof. Schapery's theory in further studies of rise time effects.

[2]Schapery, R. A., "On the Characterization of Nonlinear Viscoelastic Materials", Polymer Eng. Sci., Vol. 9, pp 295-310, 1969.

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